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Absolute magnitudes and slope parameters for 250,000 asteroids observed by Pan-STARRS PS1 – Preliminary results

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ABSTRACT

We present the results of a Monte Carlo technique to calculate the absolute magnitudes (H) and slope parameters (G) of ~240,000 asteroids observed by the Pan-STARRS1 telescope during the first 15 months of its 3-year all-sky survey mission. The system's exquisite photometry with photometric errors $\lesssim 0.04$ mag, and well-defined filter and photometric system, allowed us to derive accurate H and G even with a limited number of observations and restricted range in phase angles. Our Monte Carlo method simulates each asteroid's rotation period, amplitude and color to derive the most-likely H and G, but its major advantage is in estimating realistic statistical + systematic uncertainties and errors on each parameter. The method was tested by comparison with the well-established and accurate results for about 500 asteroids provided by Pravec et al. (Pravec, P. et al. [2012]. Icarus 221, 365–387) and then applied to determining H and G for the Pan-STARRS1 asteroids using both the Muinonen et al. (Muinonen, K. et al. [2010]. Icarus 209, 542–555) and Bowell et al. (Bowell, E. et al. [1989]. Asteroids III, Chapter Application of Photometric Models to Asteroids. University of Arizona Press, pp. 524–555) phase functions. Our results confirm the bias in MPC photometry discovered by Jurić et al. (Jurić, M. et al. [2002]. Astrophys. J. 124, 1776–1787).

1. Introduction

Asteroid diameters are critical to understanding their dynamical and morphological evolution, potential as spacecraft targets, impact threat, and much more, yet most asteroid diameters are uncertain by >50% because of the difficulties involved in calculating diameter from apparent brightness. The problem is that an asteroid's apparent brightness is a complicated function of the observing geometry, their irregular shapes, rotation phase, albedo, lack of atmosphere, and their rough, regolith-covered surfaces. Most of these data are unknown for most asteroids. The issue has been further confused because cataloged apparent magnitudes for individual asteroids may have been reported by numerous observers and observatories over many years (even decades) in a variety of photometric systems with varying concern for ensuring accuracy and precision. This work describes our process for calculating asteroid absolute magnitudes (from which diameter is calculated) and their statistical and systematic uncertainties for hundreds of thousands of asteroids using sparse but accurate and precise data from a single observatory, the Pan-STARRS1 facility on Maui, HI, USA. Our technique is suited to estimating absolute magnitudes when the phase curve coverage is even more sparse than those obtained by the Palomar Transient Factory (Law et al., 2009).

An asteroid's absolute magnitude, H, is the apparent Johnson V band magnitude, m, it would have if observed from the Sun at a distance of 1 au (i.e. observed at zero phase angle and 1 au distance). Accurate measurements of H as a function of time, together

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with infrared, polarimetric and radiometric observations, can provide crucial information about an asteroid's size and shape, geometric albedo, surface properties and spin characteristics.

In 1985 the International Astronomical Union (IAU) adopted the two-parameter phase function developed by Bowell et al. (1989, hereafter B89), $\Phi_B(\alpha; H_B, G_B)$, describing the behavior of the apparent magnitude:

$$m(r, \Delta; H_B, G_B) = 5\log(r\Delta) + \Phi_B(\alpha; H_B, G_B) \quad (1)$$

where Δ represents the topocentric distance, r the heliocentric distance, and $\alpha(r, \Delta)$ is the phase angle, the angle between the Earth and Sun as observed from the asteroid. We denote absolute magnitude in the B89 system as H_B with a corresponding slope parameter, G_B, that depends in a non-analytical manner on (at least) an asteroid's albedo and spectral type (B89; Lagerkvist and Magnusson, 1990). The slope parameter determines how strongly the apparent brightness of an asteroid depends on the phase angle and accounts for the properties of scattered light on the asteroid's surfaces. G_B has an average value of ~ 0.15 (B89) for the most numerous S and C-class main belt asteroid taxonomies. An accurate determination of both H_B and G_B requires a wide and dense time coverage of the object's apparent magnitude. Therefore, it is not surprising that only a few tens of slope parameters were measured before the advent of dedicated CCD asteroid surveys.

The B89 phase function was very successful, but observations in the past twenty years have shown it cannot reproduce the opposition brightening of E-type asteroids, the linear phase curve of the F-type asteroids, and fails to accurately predict the apparent brightness of asteroids at small phase angles. To address these issues Muinonen et al. (2010, hereafter M10) introduced an alternative phase function, ϕ_M, with two slope parameters, G_1 and G_2 that uses cubic splines to more accurately describe the behavior of the apparent magnitude. An alternative M10 formulation with a single slope parameter, G_{12} that is denoted in our work as G_M, can be used when the data are not sufficient to derive the values of the two-parameter formulation, i.e. $m = 5\log(r\Delta) + \Phi_M(\alpha; H_M, G_M)$. Their phase function was constructed such that $H_M \sim H_B$ and the average asteroid would have a slope parameter of $G_M \sim 0.5$. This form of the phase function can provide better apparent magnitude predictions but derivation of H_M and G_M still requires extensive light curve coverage and well-calibrated observational data (Oszkiewicz et al., 2012). The IAU adopted the M10 $(H, G1, G2)$ system as the new photometric system for asteroids in 2012.

In the remainder of this work we use H and G to represent 'generic' absolute magnitudes and slope parameters respectively, and use the subscripts B and M on each parameter when referring to the values calculated using the B89 and M10 phase functions respectively. We implemented both functions to facilitate comparison with (1) past work that used the B89 parameterization and (2) future work that will use the now-standard M10 implementation. When we use G_M we specifically mean the M10 G_{12} parameter.

The accuracy of most reported absolute magnitudes is poor due to the lack of good photometry and limited phase curve coverage. Jurić et al. (2002, e.g.) first reported a systematic error of about 0.4 mag in the MPC's absolute magnitudes which the MPC (and others) now attempt to address with observatory-dependent corrections to the reported apparent magnitudes.

The determination of G has traditionally been even more of a challenge – they are so difficult to measure that they have only been calculated for $\ll 0.1\%$ of asteroids and, even then, the uncertainty is usually large (Pravec et al., 2012). An accurate measurement requires dense coverage of the phase curve and observations at different viewing aspects on the asteroid, i.e. sub-solar positions. The vast majority of asteroids have no measured slope parameter so the average values of $G_B = 0.15$ or $G_M = 0.5$ are used. This assumption translates into a systematic error in an individual asteroid's H and G, and large uncertainty on the distribution of the parameters in the population. The problem is particularly acute for objects that have been observed only at large phase angles, e.g. resonant objects like 3753 Cruithne (de la Fuente Marcos and de la Fuente Marcos, 2013; Wiegert et al., 1997), and objects that orbit the Sun entirely within Earth's orbit (Zavodny et al., 2008) for which absolute magnitudes might be in error by up to about 1 mag.

In summary, the problems with our current knowledge of asteroid absolute magnitudes and slope parameters are due to:

1. Reporting observations to the Minor Planet Center (MPC) in non-standard filters and/or without accurate calibration.
2. Not performing the color transformation from the filter used for an observation to the Johnson V band for an asteroid's (usually unknown) color.
3. The lack of information about the photometric uncertainty on each observation reported to the MPC so that it must be statistically 'back-calculated' for each observatory (or observer) from historical observations.
4. The MPC database storing photometric values with only 0.1 mag precision.
5. Assuming that $G_B = 0.15$ for all asteroids that do not have a reported value for the slope parameter.
6. Sparse observations (in time). The lack of information about their rotation amplitudes induces an error and uncertainty in H.
7. Selection effects (Jedicke et al., 2002) that bias the discovery of asteroids towards their rotation amplitude maxima which induce a systematic error in their derived H.
8. Most of the effort in deriving H and G focuses on their statistical uncertainties when the systematic uncertainties dominate.

In this work we address each of these issues and derive the (H_B, G_B) and (H_M, G_M) parameters for known asteroids in the inner Solar System out to, and including, Jupiter's Trojan asteroids. All the data were acquired by a single wide-field survey, Pan-STARRS1 (Kaiser et al., 2010), in standard filters with measured transformations to an accepted photometric system yielding photometric uncertainties that are typically about an order of magnitude smaller than earlier surveys. We use a Monte Carlo technique to measure the systematic errors introduced by filter transformations for unknown spectral types, unknown G, and the unknown asteroid spin and amplitude.

2. Pan-STARRS1 asteroids

The Panoramic Survey Telescope and Rapid Response System's prototype telescope (Pan-STARRS1; Kaiser et al., 2010) was operated by the PS1 Science Consortium during the time period in which the data used in this study was acquired. The telescope has a 1.4 gigapixel camera (Tonry and Onaka, 2009) and 1.8 m f/4 Ritchey-Chretien optical assembly and has been surveying the sky since the second half of 2011. Although the scientific scope of the survey is wide – including the Solar System, exoplanets, brown dwarfs, stellar astronomy, galaxies, cosmology, etc. – most of the data products are suitable for asteroid science. About 5% of the survey time was dedicated to the 'Solar System' (SS) survey (more accurately a survey for near-Earth objects, NEO) through the end of 2012, was increased to about 11% from then till 2014 March 31, and the system is now 100% dedicated to NEO surveying.

Pan-STARRS1 surveys in six broadband filters, four of which were designed to be similar to the Sloan Digital Sky Survey photometric system (SDSS; Fukugita et al., 1996). Most of the observing time was devoted to the 3π survey of the sky north of -30° declination for which each field was observed up to 20×/year in each of 5 filters – g_{P1}, r_{P1}, i_{P1}, z_{P1} and y_{P1}. In the 3π survey the same field is